The energy and material related impacts of the transition towards low-carbon heating: a case study of the Netherlands

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Chapter 3

Alternatives for Natural Gas-Based Heating Systems, a Quantitative GIS Based Analysis of Climate Impacts and Financial Feasibility

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Abstract

The heating of buildings currently produces six percent of global greenhouse gas emissions. Sustainable heating technologies can reduce heating-related CO_2 emissions by up to 90%. We present a Python-based GIS-model to analyse the environmental and financial impact of strategies to reduce heating-related CO_2 emissions of residential buildings. The city-wide implementation of three alternatives to natural gas are evaluated: high temperature heating networks, low temperature heating networks, and heat pumps. We find that both lowering the demand for heat and providing more sustainable sources of heat will be necessary to achieve significant CO_2 emission reductions. Of the studied alternatives, only low temperature heating networks and heat pumps have the potential to reduce CO_2 emissions by 90%. A CO_2 tax and an increase in tax on the use of natural gas are potent policy tools to accelerate the adoption of low-carbon heating technologies.

3.1 Introduction

Urban heating is responsible for six percent of global GHG emissions (Intergovernmental Panel on Climate Change & Edenhofer, 2014). In Europe, the use of natural gas for urban heating has been steadily increasing in the last decades, currently providing 68% of urban heat. Of the European countries, Germany and the Netherlands are amongst those most reliant on fossil fuels, with more than 90% of their heat supplied by natural gas (Persson & Werner, 2015). Reducing CO_2 emissions from urban heating will therefore involve transitioning away from fossil fuel-based urban heating technologies.

The Netherlands is an interesting contemporary case study. Its urban heating sector is responsible for 36% of overall Dutch CO_2 emissions (ECN & CBS, 2017). In 2017, the political decision was taken to transition towards fossil-free urban heating, on a very ambitious time-schedule: heating-related CO_2 emissions should be reduced by 49% before 2030, and 90% before 2050 (Rijksoverheid, 2017). This is referred to as the '*warmtetransitie*', or heating transition. Besides reducing GHG emissions, the Netherlands is concerned with intensifying earthquake activity related to the extraction of natural gas. In 2018, over 90 earthquakes have been recorded in the Groningen region, which is responsible for the bulk of the Dutch domestic natural gas production (KNMI, 2020).

There are three often discussed alternatives to fossil-fuel based heating systems: high-temperature heating networks (HT, supply temperature of around 85 °C), low-temperature heating networks (LT, supply temperature of around 55 °C), and heat pumps (Petrović & Karlsson, 2016; Werner, 2018). Heating networks (also known as district heating) are based on a central heat source and a network of underground water pipes to distribute the heat. Sources of heat include combined heat and power plants (gas, coal, biomass), industrial waste heat and geothermal heat (Lund et al., 2014). Heat pumps use electricity to transfer heat from an outside source, such as the air or water (either stored for this particular purpose or surface water), to a building. There is a wide variety of heat pump technologies available, ranging from small air-to-air heat pumps to large water-to-water heat pumps capable of delivering heat to multiple homes. The Dutch government is considering these three often discussed technologies as viable replacements for the current gas-based heating system (Rijksoverheid, 2017). In this work, we explore their environmental and financial consequences in the context of the Dutch heating transition.

One of the first steps in achieving a reduction in urban heat consumption is improving the insulation of the building stock. Although this will provide a significant reduction of emissions (38-59%), it is not enough to reach the climate goals determined by policy (Buffat et al., 2017; Francisco Pinto & Carrilho da Graça, 2018; Werner, 2018).

In literature, we find considerable CO_2 emission reductions (20-70%) across different alternative heating technologies (Bianco et al., 2017; Delmastro et al., 2016; Lund et al., 2014; Persson & Werner, 2015; Sayegh et al., 2018). However, comparing technologies across different countries is difficult. Their performance is dependent on the climate of the country and the available sources of heat. Furthermore, these comparisons often exclude the effects of increased insulation and the required additional infrastructure. Conclusions about the overall CO_2 reduction potential of alternative heating technologies can only be drawn after a consistent system analysis.

As alternative heating technologies do not operate on natural gas, they require different supporting infrastructures. Heat pumps use the electricity grid, while HT and LT heating networks utilize specific heating networks. This change in infrastructure is generally not taken into account in the assessment of the impact of these technologies. We are aware of only one paper: Love et al. (2017) that established the possible impact of heat pumps on the electricity grid. They found that the peak grid demand could increase substantially as a result of implementing heat pumps.

A large-scale change of the heating system is costly and will require investments over a long period of time. It is therefore critical to assess both the technical and financial feasibility of this transition before making irreversible policy choices. The main factor in establishing the price of heat delivered by heating networks is the cost of infrastructure. Further factors influencing the total cost of a system-wide heating technology replacement are determined by retrofitting buildings and the replacement of the heating technology. Even though financial insight in this transition is crucial for its implementation, system-wide costs including infrastructure are seldom mentioned in the literature (Buffat et al., 2017; Francisco Pinto & Carrilho da Graça, 2018; Serrano-Jimenez et al., 2017; Werner, 2018).

Research related to alternative heating technologies has focused on individual technological implementations across different countries, making it difficult to compare their CO_2-emission reduction potentials. This body of literature contributes significantly to the understanding and solving of the multifaceted challenge of the heating transition. However, these models only discuss building refurbishment options and/or a single alternative heating technologies, while the desired situation of the overall heating system could be a combination of these (Bokhoven & D, 2018).

In addition, the literature has not addressed the system-wide reduction of heating-related CO_2 emissions. The financial implications of sustainable heating technologies are similarly not included in a system-wide analysis. It is therefore unclear how much the emissions related to urban heating can be reduced and what the financial impact of different technologies would be. Especially for home-owners, the heating transition could prove to be an unexpected financial burden (Rijksoverheid, 2017).

We use a bottom-up model based on GIS data to examine the environmental and financial aspects of sustainable heating technologies on a city-wide scale. We evaluate HT and LT heating networks with heat pumps as an alternative to natural gas for the heating of residential buildings. Building retrofitting and the different infrastructures required are also included in our analysis. The climate goals set by the Dutch government will be used as a basis for comparison

3.2 Method

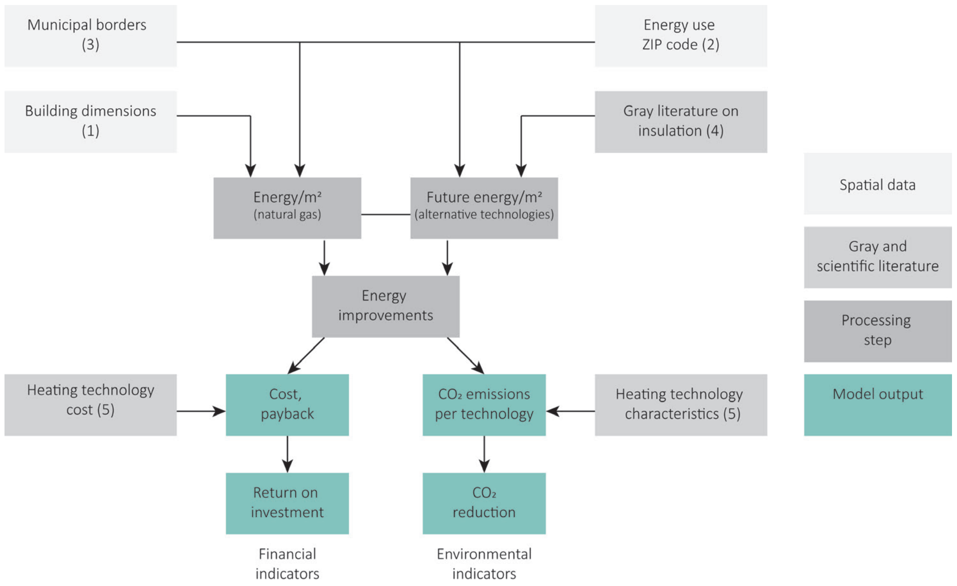
Through literature research we identified a selection of heating technologies that can act as a more sustainable replacement to the existing fossil-fuel based heating systems. Through the use of public GIS-data, we were able to analyse the impact of each technology on the Dutch built environment on a city-wide scale. In order to compare the impact each technology, we developed a Python-based model. We used GeoPandas, an open-source GIS Python package, to analyse multiple GIS-datasets. First, two spatial datasets were merged to create one coherent dataset containing building information. Second, the current and future energy consumption of buildings was calculated. Third, this information was used to determine the CO_2 emissions, operating costs and total investment cost. Finally, the return on investment and CO_2 reduction potential in comparison with the existing natural gas network was calculated. An overview of our model is shown in Figure 5, visualizing data flows and sources.

The Dutch government has placed the responsibility for the implementation of this heating transition on its local governments. Current policy plans focus on the replacement of heating technologies on a city-district scale. For the case study of our research, the city of The Hague is used because it represents a typical Dutch city with an old historical centre and a variety of building types in its outskirts.

3.2.1 Technologies

The current plan to replace natural gas for the most densely urbanised areas of the Netherlands is mostly based on using large scale HT heating networks. This network is envisioned to use waste heat from industrial areas to supply heat to multiple cities (known as the *warmterotonde*, or 'heating-roundabout' in the Netherlands). The use of these thermal sources is controversial, as this heat will mostly be sourced from refineries and other fossil-fuel related industries, potentially creating a technological lock-in with fossil energy sources (Ensoc & RVO, 2018).

The use of water-to-water heat pumps with a 12-kW heating capacity (around 200 m^2 of functional floor area) was assumed. Other heat pump technologies are available with different price ranges. However, these alternatives are more susceptible to extreme cold weather due to their dependency on the outside temperature (Petrović & Karlsson, 2016). Other heating technologies such as pebble heaters, electric resistance heaters, solar boilers, and infrared panels are considered as supporting technology and not capable of fully replacing natural gas as the main heating technology for a building (RvO, 2018).



Number	Data used	Processing steps	Source
1. Building dimensions	BAG3D GIS-dataset	Clipping to municipal border and spatial join with the energy use per ZIP code	(Kadaster, 2018)
2. Energy use per ZIP code	Gas & Elektra GIS-dataset	Clipping to municipal border and spatial join with the BAG3D dataset	(CBS, 2019b)
3. Municipal borders	CBS Wijk en buurtkaart 2017 GIS-dataset	Outline for the clipping of the datasets	(CBS, 2019a)
4. Grey literature on insulation	Building renovation steps & cost	Technological parameters used in the model	Appendix AII.V
5. Heating technologies characteristics	Multiple sources	Technological parameters used in the model	Table 1 & 2

Figure 5, overview of the information flows in the model:

Our analysis includes the infrastructure transporting the energy from the source to the residential buildings. Infrastructure investment in the electricity grid together with the digging of a well for heat pumps were taken into account. For the heating networks, the implementation of a city-wide heating network was assumed. Replacement of the in-house heating system (existing radiators) with an LT heating system was included in the calculation for the LT heating networks and heat pumps. For the HT heating network, we assumed that the old HT heating system remained sufficient as these are often oversized for reliability (Nord, 2016). All assumptions regarding the alternative heating technologies are available in Appendix AII.II.

3.2.1.1 Calculation of current and future heat demand

Building gas consumption (m^3/year) was compared with the potential future reduction in this heat demand. Natural gas consumption was converted from m^3 gas to kWh/m^2 on an annual basis. This calculation of the urban energy consumption was based on the paper by Nouvel et al., (2015). Different technologies and their energy sources are simpler to compare using kWh/m^2. The future heat demand was calculated and based on retrofitted buildings: including an increase in insulation, replacement of the heating technology and heating system.

The future heat consumption of the residential buildings was assumed to be around 70 kWh/m^2 per year after improving the insulation. This is roughly comparable to the average thermal performance the Dutch government aims to achieve for their future built environment (Rijksoverheid, 2017). This improvement in the thermal performance of a building also reduces the impact of a very harsh winter, which some alternative heating technologies are vulnerable to (Werner, 2018). Building heat demand improvements due to insulation were calculated as follows:

$$Future\ heat\ demand\ (70)\left(\frac{\frac{kWh}{m^2}}{year}\right) = Current\ heat\ demand\left(\frac{\frac{kWh}{m^2}}{year}\right) - insulation\ improvements\left(\frac{\frac{kWh}{m^2}}{year}\right) \quad (1)$$

This difference in heat demand was used to determine the investment cost of insulation. Buildings were not given an increased amount of insulation in the model when consuming less than 70 kWh/m^2 per year.

3.2.1.2 Calculation of CO_2 reduction potential

In order to determine the CO_2 reduction potential of each alternative heating technology, the change in heating demand through insulation, the replacement of the heating technology and the efficiency of the corresponding infrastructure was evaluated. Each alternative heating technology was compared to the CO_2 intensity (g CO_2/kWh) of the existing natural gas system. Based on the reduction potential of each technology, we identified city districts most suitable for a certain alternative heating technology.

A coefficient of performance (COP) was used to describe the energy efficiency of the technology and infrastructure. Heating network transportation losses were assumed to be between 12 and 24%, depending on the technology (Lund et al., 2014). The lower value of 12% was used as the network losses for the LT networks, while the higher value of 24% was used for the HT networks. The heat pumps also have transportation losses from the electricity network, although these will be more marginal (Love et al., 2017). As a result, in the model, the CO_2 reduction is calculated as follows

$$CO_2\ reduction\ \left(\frac{kg}{year}\right) = \frac{Heat\ demand\ (kWh/year)}{COP} * CO_2\ intensity\ (\frac{kg}{kWh}) \quad (2)$$

where the future heat demand of a building is used in kWh/m^2/year, COP as the efficiency of the technology and infrastructure, and the CO_2 intensity the CO_2-emissions of the used energy source in comparison with natural gas. The calculation of these CO_2 intensity values is shown in section 3.2.2, scenarios.

3.2.1.3 Calculation of investment cost and return on investment

For the return on investment, the total operating costs of running a natural gas-powered heating system was compared with the required investment and operating cost of the alternative technologies. The total investment cost in € per technology is defined as

$$Investment\ (€)\ = C_{retrofit} + C_{heatsys} + C_{technology} + C_{\mathrm{infra}} \quad (3)$$

The investment cost was calculated per building by taking the building retrofitting cost, replacement of in-house heating systems and the addition of a heat pump and/or heating network infrastructure. An overview of these costs is shown in Appendix AII.I.

Alternative technologies operating costs were based upon replacement costs, consumption of electricity or network heat with the improved insulation and standing charges. The replacement cost of the boiler, the consumption of natural gas and the standing charges were included. Current and potential future prices of heat, gas, and electricity were included to predict the influence of changing prices of energy on the overall system. A return on investment (ROI) per technology was calculated from the payback over 30 years (2020-2050) and the total investment costs.

For the replacement cost, a 15-year lifetime was assumed for both appliances, while for the heating networks a 50-year lifetime was used. For LT and HT heating networks the infrastructure investments were based on a large scale heating network project in the Netherlands (CE Delft, 2016). There is however a lack of sources to compare this number with. To illustrate which stakeholder (home-owners and heating network companies/government) will most likely pay for the technology, a breakdown of this investment cost per building was used. In Appendix AII.II, an overview is given of the cost per technology and sources.

3.2.2 Scenarios

Reduction in emissions and the pricing of alternative heating technologies determine their viability as an alternative to natural gas. Development of energy prices and possible governmental interventions influence the affordability and ROI of technologies. Furthermore, the source of heat for each chosen technology influences its CO_2 emission reduction potential. Its viability as an alternative to natural gas can be explored by looking into potential future developments. For all the technologies, we assume a city-wide implementation.

3.2.2.1 Available sources of heat

The three mentioned alternative heating technologies operate with different sources of heat. For this analysis, the most widely available sources and potentially sustainable sources of heat available in the Netherlands were evaluated (TNO, 2017). These sources of heat range from grey electricity to the use of PV panels for the heat pumps, geothermal and sustainable heat sources for the LT heating networks, and CC power generation and HT waste heat for the HT heating networks. An overview of these sources of heat and their CO_2 emissions per kWh of urban heat for heating networks are given in table 5. These sources of heat were compared based on a direct implementation of the technology and its source of heat.

In the first section of the results these sources of heat are compared in a city-wide implementation for each heating technology based on their current and potential CO_2 reductions. A steady-state implementation from 2020-2050 was assumed. The average CO_2 production per building in the case study is shown for each technology and source of heat. Additionally, these results are compared with the climate goals for 2030 and 2050 of the Dutch government.

Table 5a, CO_2 intensity per kWh of supplied heat for heating networks and heat pumps sources (MRA & TNO, 2017) (Stimular, 2016):

Energy source	Gram CO_2/GJ	gram CO_2/ kWh heat	CO_2 intensity (natural gas = 1)	Temperature
Natural gas		192.8	1	N/A
Biomass	13000	46.8	0.24	LT
Waste heat without additional burning	8800	31.7	0.16	LT
Geothermal	25050	90.1	0.47	LT
Heat from burning waste	26000	93.6	0.49	HT
Waste heat Tata Steel	26000	93.6	0.49	HT
Waste heat from gas fired power plant	32000	115.2	0.60	HT
Waste heat from coal fired power plant	45000	162.0	0.84	HT

Table 5b, CO_2 intensity per kWh of supplied heat for heat pumps (COP = 3.5):

Energy source	Gram CO_2/kWh electricity	gram CO_2/kWh heat	CO_2 intensity (natural gas = 1)
PV	50	14.3	0.07
'Grey' electricity	365.83	104.5	0.54

3.2.2.2 Cost effectiveness scenarios

Pricing is often used by governments as a method to regulate policy. The alternative heating technologies and possible future interventions of the government should also be included in the analysis to assess their cost-effectiveness. Examples of these pricing methods are: (a) the increase of the price of natural gas to promote the transition to alternative energy technologies, (b) increasing the tax on heat to stimulate the installation of insulation and more energy-efficient heating technologies, and (c) a CO_2 tax to make the reduction of CO_2 emissions more financially attractive. To implement these possible developments in the model, the following scenarios were used:

- An increased price of natural gas, 20% and 50% on average until 2050.
- A CO_2 tax of 50 euro per metric ton CO_2, and 80 euro per metric ton CO_2 (EU, 2016).
- Increased tax on heat with an average increase of 20% and 50% until 2050.

An overview of the impact of these scenarios on the input parameters is given in Table 6.

Another aspect of an alternative heating technology is its total investment cost. The build-up of the pricing of each technology is described in section 3.2.2.3. It is also possible that the overall cost is higher or lower than we anticipated in this research. To address this uncertainty, we included three investment cost ranges: the standard, low and high cost. For these low and high ranges, the total alternative heating technologies investment cost is varied with -5000 and +5000 euro to account for the uncertainty in technology and infrastructure pricing.

In the second section of the results, we compare the return on investment (ROI) across the cost effectiveness scenarios and the total cost ranges of the alternative heating technologies.

3.2.3 Data selection

The spatial datasets were supplied to us on a ZIP-code 6 level due to privacy concerns. On this spatial resolution, it was not possible to identify the different types of buildings and their age. As a result, the calculation of the future energy demand and potential reduction of CO_2 emissions was aggregated and less accurate for a building-level analysis. Buildings in the dataset with a residential occupancy and existing connection to the gas network were selected. The number of households per zip code is derived from the number of existing connections to the gas network.

Table 6, input parameters for each scenario:

	Cost effectiveness scenarios						
	Baseline	CO_2 tax low	CO_2 tax high	Price of natural gas +20%	Price of natural gas +50%	Increased heat tax +20%	Increased heat tax +50%
Price of natural gas (€/m3)	0.67	0.67	0.67	0.80	1.01	0.73	0.83
Price of electricity (€/kWh)	0.21	0.21	0.21	0.21	0.21	0.22	0.23
Price heating network heat (€/kWh)	0.067	0.067	0.067	0.067	0.067	0.067	0.067
CO_2 tax (€/ metric ton CO_2)	0	40	80	0	0	0	0

The datasets used in this model have their limitations. Occasionally the data was incomplete or inaccurate, skewing the results of our model. To extract these outliers, a filter on buildings with less than 200 m^3 of gas consumption per year or >400 kWh/m^2 per year was used. From the original 83.343 residential buildings in the dataset 66.598 were included in the model after removing incomplete or faulty datapoints. The original datasets were clipped to the boundaries of the case study to accommodate for more effective file size and processing time. Additionally, to determine the most influential input parameters a localized sensitivity analysis was used. The input values of the model were used for the baseline scenario, while these were adjusted with -10% and +10% to determine their impact on the output. The python code (named Python_code_appendix) and the output of the GIS model (named JIE_GIS_data) are included in Appendix II.

3.3 Results

3.3.1 The CO_2 emission reduction potential

Across all alternative heating technologies, we find that the CO_2 reduction potentials range from 41% to 95% (Figure 6). For HT heating networks, the CO_2 reduction potential ranges from 41% with heat from CC power generation (coal) to 65% with heat coming from waste incineration. For LT heating networks, the residential CO_2 production is reduced by 65% with a geothermal source and 90% when utilizing sustainable waste heat. Heat pumps with 'grey' electricity decreases the CO_2 emissions with 60%, which further decreases to 95% when electricity from PV panels is used.

Another important aspect is the CO_2 reduction from the improved insulation of a building. In Figure 2 we show that 33% of the reduction of annual CO_2 is achieved by the improved insulation. This reduction is identical for each technology as they use the same assumptions for the insulation and has nothing to do with the chosen technology.

With the more sustainable sources of heat (lower CO_2 emissions per kWh of supplied heat), LT heating networks and heat pumps are capable of reaching the required 90% reduction in CO_2 emissions. It is also worth mentioning that without the increased insulation, none of the heating technologies and sources will be sufficient for the 2050 climate goal. Besides replacement of the heating technology and source of heat, a reduction in the overall heating demand is required.

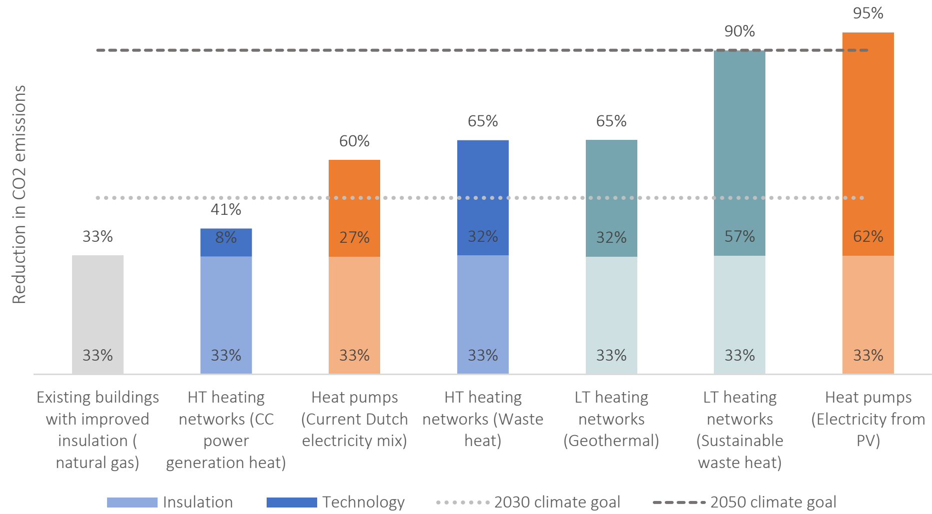


Figure 6, the impact of different sources of heat per technology on the CO_2 reduction:

Based on the spatial results shown in Figure 7, we identify several city districts particularly suitable for a particular sustainable heating technology. Some districts will still have a relatively high heat demand (mostly older buildings), even after refurbishment, and will therefore be more suited for a HT heating network. The distribution of the CO_2 emission reduction potential of the LT heating networks and the heat pumps are more evenly matched. The choice for these technologies will have to be based on the availability of local sources of heat. It is most likely that a combination of the technologies will eventually replace the current city-wide natural gas-based system.

3.3.2 ROI and investment cost

3.3.2.1 Return on investment

The ROI varies from -86% up to 28% across all technologies and scenarios. The ROI, calculated in the model for 3 different investment ranges and 7 future scenarios are shown in Figure 8. We find that in all scenarios the heat pumps have the highest ROI, ranging from -64% in the 'high-cost' baseline scenario, up to 28% in the most optimistic 'low-cost +50% price increase for the natural gas' scenario. Also, in this technology, the highest disparity between the different results is found. The LT heating networks ROI ranges from -74% for the high-cost baseline scenario and up to -1% in the low-cost scenario with a 50% price increase for natural gas. The variation of the ROI in the HT heating networks ranges from -86% in the high-cost baseline scenario up to -7% in the low-cost +50% price of natural gas scenario.

Even with economic incentives, none of the alternative heating technologies has a positive ROI. Only in a low-cost investment range and with a significant increase in the price of natural gas do the heat pumps have the potential to break even or generate a small profit.

3.3.2.2 Investment costs

Investment costs range from €37,000 to €44,000 between the technologies. Figure 8 provides a comparison of the investment per building for each technology in the standard cost baseline scenario. The investment per building for the heat pumps is the highest with €44,000, but still comparable with the HT-heating networks €40,000. LT-heating networks require €37,000 per building. From this result and figure 9 it becomes apparent that although heat pumps have the highest relative payback, only in very specific set of circumstances will this technology have a positive return on investment. Implementation across an entire city will require significant investment. In our case study, The Hague, investment costs range from 1.73 billion to 2.91 billion euros.

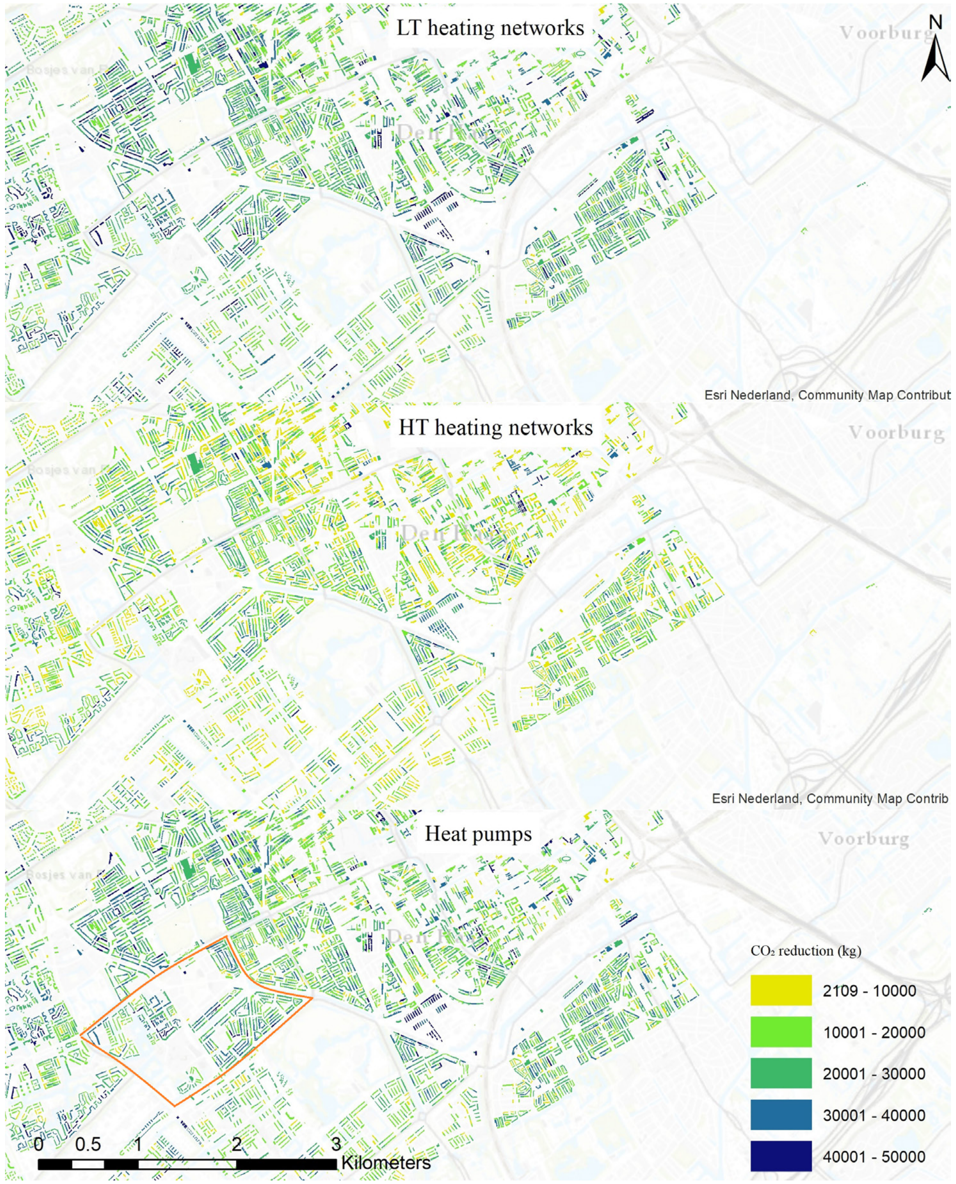


Figure 7, Annual CO_2 reduction potential for the alternative heating technologies per ZIP code in the city of The Hague (city districts best suited for a certain technology highlighted in orange): (a) LT heating networks; (b) HT heating networks; (c) Heat pumps.

The cost attributed to infrastructure improvements differs strongly per technology. For the heat pumps, €10,000 per building is required to improve the electricity network and dig a well. The cost of the heat pumps is the biggest factor in this technology as €23,000 per building is required. Both the heating network technologies require

€26,000 per building to construct the infrastructure. For the heating networks, this is the biggest expense. For each alternative heating technology, the investment in insulation for the case study is €10,700 per building. The technological investment for the LT and HT heating network technologies is between €175 and €4,000 per building. An overview of the investment per technology and subsections can be found in Appendix AII.II.

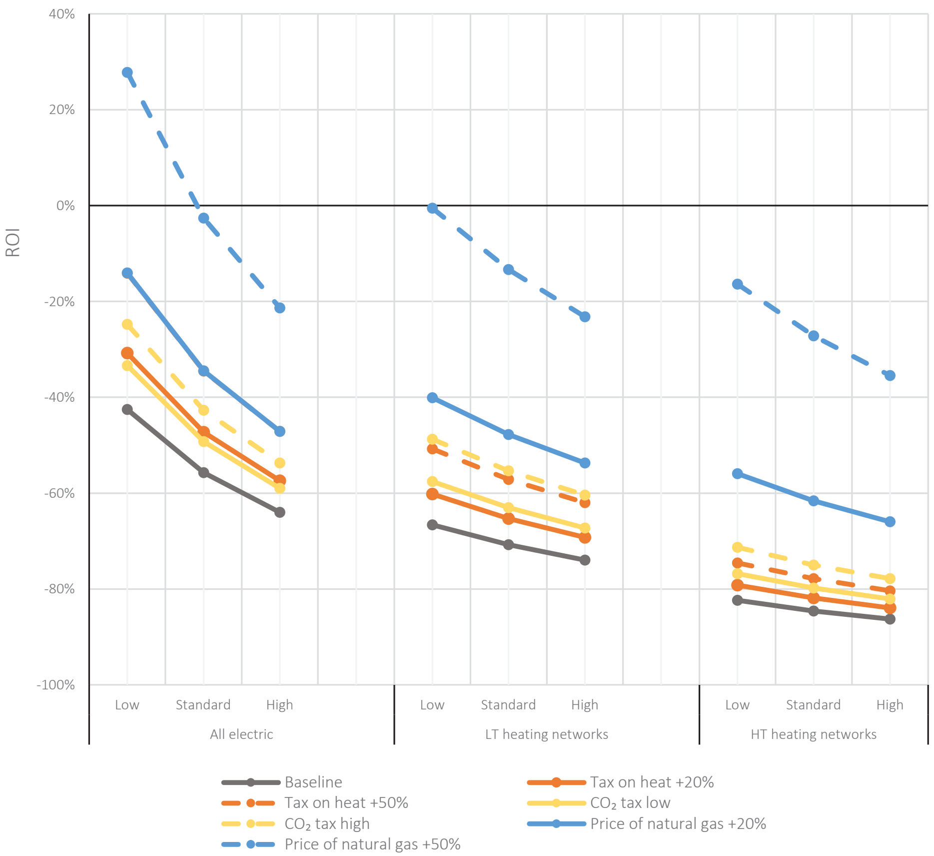


Figure 8, return on investment over 30 years for each investment range and cost effectiveness scenario in % (higher is better, tabular form provided in supporting information 6):

In the Dutch context, home-owners will pay for insulation and replacement of the heating technology, while the government and energy companies are responsible for infrastructure investments. Therefore, home-owners will be investing €15,000 for the heating network technologies and €34,000 for the heat pump technology. The government and/or energy companies will be investing €26,000 per building for the heating networks scenario and €10,000 for the heat pump scenario. Infrastructure investment has the most influence on the cost of the heating networks, considerably increasing their overall cost.

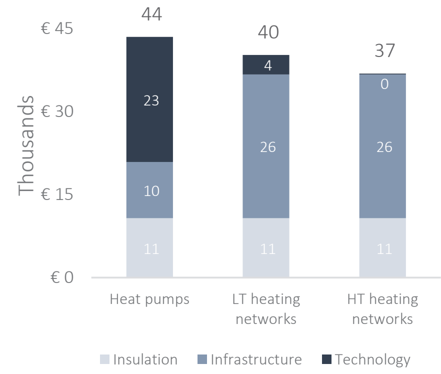


Figure 9, average investment cost in the standard cost scenario per building:

The results show that even with economic incentives the alternative heating technologies have a difficult business case. Only in the best-case scenario when the heat pumps are cheaper than expected, and with a significant increase in the price of gas will the technology investment generate a small return on investment. This means that, in contrast to insulation, the incentive to utilize alternative heating technologies will have to be different for home-owners. For example, making these technologies mandatory for newly constructed buildings and implementing subsidies from the government for the current building stock.

3.3.3 Sensitivity of the input parameters

Adjusting the input parameters with +-10%, the output of the model varied from +27% and -27%. The price of natural gas is the most influential input parameter with +-27%, while the COP varies the output with +-14% for the ROI. We show that the price per m^3 of natural gas is the most influential input parameter for this model on the ROI. This corresponds to the results in section 3.3.2, where increasing the price of natural gas with +50% leads to the highest ROI. It can also be observed that the COP has a positive influence on the CO_2 reduction. Heat pumps have a high COP in comparison with the other technologies, and consequently the highest CO_2 reduction potential. Additionally, the investment cost of the model is affected by the technology cost (infrastructure, insulations, etc), and its lifetime.

The results of the sensitivity analysis are in line with the high impact of the price of natural gas on the ROI in figure 10. The relatively high impact of the COP on the ROI also explains why the heat pumps generate the most ROI of all the alternative heating technologies.

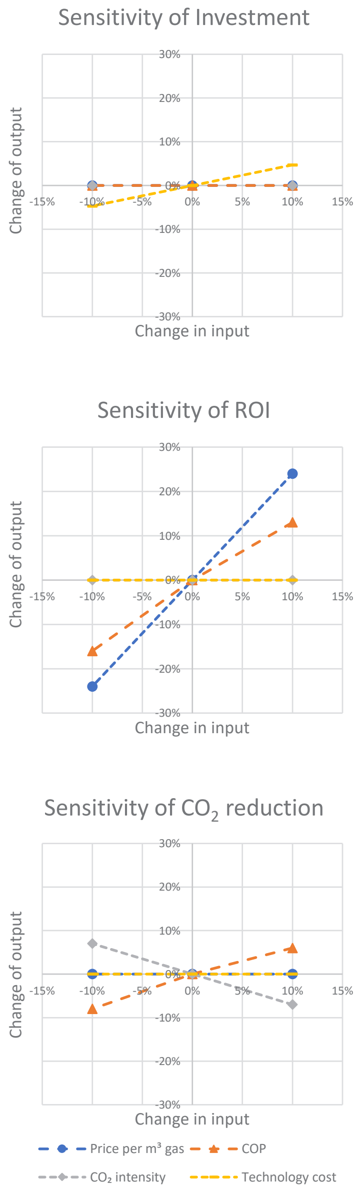


Figure 10, Sensitivity of the input parameters on the output of the model, (tabular form provided in Appendix AII.VI): (a) sensitivity of investment; (b) sensitivity of ROI; (c) sensitivity of CO_2 reduction

3.4 Discussion

Achieving a 90% reduction of CO_2 emissions requires a drastic change in the current Dutch heating infrastructure. This study provides a GIS-based model that clarifies the environmental and financial implications of the Dutch heating transition. We compared the implementation of HT heating networks with LT heating networks and water-to-water heat pumps on a city-wide scale. Besides contributing to the understanding of the 2030 and 2050 climate goals, the financial impact is shown to be of importance for multiple stakeholders in this research.

Through the modelling of the three selected technologies and the evaluation of multiple scenarios, we show that LT heating networks and heat pumps both have the potential to reach the Paris agreement goal (90% reduction of CO_2 emissions before 2050). HT heating networks could reach the 2030 climate goal (49% reduction of CO_2 emissions), but would significantly limit further reductions. Our findings underline the importance of the sources of heat in reducing the CO_2 impact of residential heating.

We show that the return on investment is generally negative for all technologies over 30 years if no changes are made to energy prices and taxes. Government intervention is required to improve the business case for alternative heating technologies and accelerate the heating transition. The total investment of around €40,000 per building is quite similar for each technology. The heat pump and digging of a well largely determine the investment cost for the heat pump technology. Most of the heat pump investments required for a building are likely going to be paid for by the home-owners, making it difficult to implement on a centralized large-scale. For the heating networks, the infrastructure investment dictates most of the costs. Also, the heating network infrastructure will be government-funded or laid down by the heating network companies, lowering the investment for the home-owner significant. Nonetheless, it is doubtful that every Dutch home-owner is able and/or willing to invest €15,000-€34,000 in the next 30 years with current energy prices and taxes.

The adjustment of energy prices or a CO_2 tax has the highest impact on the ROI of the heat pumps and the LT heating networks. With the right policies and tax instruments, they could surpass the break-even point. The results further limit the affordability of the HT heating networks considering they currently even lack taxation. In our model, we also show that the price of natural gas has the highest impact on the ROI of alternative heating technologies. Currently, the energy bill of a Dutch household is largely determined by the consumption of natural gas instead of fixed tariffs. Increasing the price of natural gas improves the business case for alternative heating technologies significantly, but also makes the cost of urban heating more expensive.

We believe that this research gives some insight into the CO_2 reduction potentials for the Dutch residential building stock. Replacing heating technologies is not sufficient on its own. Acquiring more sustainable sources of urban heat is also required to achieve significant CO_2 reductions before 2050. The development of long-term spatial planning and financial incentives, in cooperation with home-owners, is essential to accelerate this heating transition. Usage of HT industrial waste heat for the 2030 climate goal could limit further reductions in CO_2 emissions and obviate the 2050 climate goal.

In comparison with previous literature, we compared the environmental and financial impact of multiple heating technologies within the same case study. This alleviates the problem of comparing heating technologies across different climates and building types. Also, the inclusion of infrastructure and multiple sources of heat in our analysis gives a broader perspective on the consequences of this adjustment to a heating system.

Although we use GIS data, our results are currently not spatially explicit, beyond visually identifying spatial patterns on a district scale. Further research could identify the buildings most suitable for adjustment to a specific alternative heating technology. For example, a spatially explicit analysis could identify buildings which would be most suitable for HT heating networks. Also, comparing these heating options with further spatial characteristics such as available sources of heat and socio-demographic characteristics would provide a more in-depth spatial analysis. A further development of indicators, and the inclusion of more alternative heating technologies would also improve the outcomes of our model.

A limitation of this study is that we relied on implied data due to a lack of information on heating networks. Especially the infrastructure prices of the heating networks are generally unspecified. The price ranges of the heat pump technology and the chosen technology could also be debated. We were also unable to include inflation in the model. Lastly, the embodied energy of alternative heating technologies and their material impact is not included. With more fitting data this methodology can be easily updated and applied to other future scenarios.

3.5 Conclusion

This study highlights the differences between three main natural gas-free heating technologies, on their environmental, technical and financial aspects. Our main results show that the business cases for the alternative heating technologies is only profitable with the right combination of economic incentives. Without significant subsidies for existing buildings and home-owners, the financial implications could prove fatal for the heating transition.

We show that low temperature (LT) heating networks and heat pumps both have the potential to reduce the Dutch urban heat-related CO_2 output by 90%. A combination of these technologies could be used as an environmental and financial alternative to natural gas. However, these replacement technologies will require a considerable capacity of sustainable sources of heat to reduce CO_2 emissions by 90%.

A combination of policies together with subsidies will give home-owners a strong incentive to refurbish their buildings and lower the residential consumption of heat. In the larger context, our study shows that using industrial HT waste heat for residential urban heating in the *warmterotonde* will not be sufficient to achieve the 2050 climate goal.

Further research in this direction is encouraged to provide multiple energy evaluation tools for the heating transition. The development of this heating transition could also be influenced by energy storage solutions. At present, the use of energy storage is limited, but in the future, this could have a strong influence on the system (Petrović & Karlsson, 2016). Phase change materials (PCM's), improvements in battery technology and localized hydrogen storage present a potentially disruptive development for the overall energy grid (heat and electricity). The material demand for such a large-scale transition of an energy system could also influence, or even disrupt critical material supply chains (Sprecher et al., 2017). These developments should be considered in future research on this topic.

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